Appendix C: Site Specific Criteria Analysis

Development of Site-Specific Total Phosphorus Criteria for Petenwell Flowage, Castle Rock Flowage, and Lake Wisconsin

Summary: Wisconsin Administrative Code NR 102.06(7) states that site-specific criteria (SSC) for total phosphorus (TP) may be adopted where site-specific data and analysis using scientifically defensible methods and sound scientific rationale demonstrate a different criterion is protective of the designated use of the specific surface water segment or waterbody. TP SSC were estimated for Petenwell Flowage, Castle Rock Flowage, and Lake Wisconsin that are expected to meet the chlorophyll *a* (CHL) target for recreational use (70^{th} percentile CHL < 20 µg/L during July 15 – September 15). The SSC are based on empirical estimates of the effects of TP concentration, river discharge, and day of year on CHL concentration. The recommended SSC for Petenwell and Castle Rock are 53 and 55 µg/L TP, respectively, as a summer (June 1 – September 15) mean concentration, which is higher than the existing criteria (40 µg/L TP). The recommended SSC for Lake Wisconsin is 47 µg/L TP, which is lower than the existing criterion (100 µg/L TP).

Reservoir Descriptions

Petenwell and Castle Rock Flowages are the largest reservoirs on the Wisconsin River, and water quality problems on these reservoirs were the primary motivation for the development of Total Maximum Daily Loads (TMDLs) for TP throughout the Wisconsin River Basin. Both reservoirs have a TP criterion of 40 µg/L as a summer (June 1 – September 15) mean concentration because they are classified as shallow (unstratified) drainage lakes. This TP criterion was primarily based on research in Minnesota[1] that showed an increase in algal blooms in shallow lakes when TP exceeds 40 µg/L. Preliminary analysis of water quality monitoring data from Petenwell and Castle Rock Flowages indicated that CHL:TP ratios are lower than average, and their relatively short water residence times are likely to limit algal growth. Therefore, a thorough SSC feasibility analysis seemed warranted.

Lake Wisconsin is classified as an impounded flowing water because its summer water residence time is less than 14 days, so its TP criterion is equal to the criterion of the inflowing river (100 µg/L). However, the current summer mean TP concentration in Lake Wisconsin is 98 µg/L, and it has frequent and severe algal blooms (mean summer CHL is 48 µg/L), so this criterion is clearly not appropriate.

Overview of Analysis

This analysis is based on four years of biweekly water quality monitoring that was conducted at 3-4 stations per reservoir during the open water seasons of 2010-2013 (Table 1). The first step in the analysis was to plot CHL concentration against several potential drivers of CHL variability, including nutrients, day of year, river discharge, and water temperature (Table 2, Figures 1-3). Next, several statistical models were fit to estimate multiple regression relationships between

[1] Minnesota Pollution Control Agency. 2005. Minnesota Lake Water Quality Assessment Report: Developing Nutrient Criteria", Third Edition.

selected variables and CHL. The best models were then used to estimate daily CHL concentrations during the open water seasons of 2010-2013, and to simulate how those concentrations would change with lower TP loading to the reservoirs.

Relationships between chlorophyll and other variables

The scatter plots of chlorophyll *a* versus other parameters in Petenwell and Castle Rock Flowages are similar, which indicates that the processes that drive algal growth are similar in the two reservoirs. As expected, there is positive correlation between TP, TN, and CHL in these reservoirs. The inorganic forms of both nutrients (PO4, NO3, and NH4) are all negatively correlated with CHL, which makes sense because as algae grow, they convert these forms to organic matter. TKN, which is primarily organic N given the mostly low NH4 concentrations, is strongly positively correlated with CHL. There is a weak positive correlation between DOC and CHL, which indicates that the upper range of DOC concentrations in these reservoirs does not limit light availability for algal growth. The plots of both TEMP and JD indicate that warmer water and/or more solar radiation are associated with higher CHL. There is a weak negative correlation between Q and CHL, although especially in Petenwell, CHL also appears to decrease at the lowest flows. There is a weak positive correlation between DO and CHL, which probably reflects the concurrent production of these two products of photosynthesis.

The scatter plots of chlorophyll *a* versus other parameters in Lake Wisconsin are mostly like those for Petenwell and Castle Rock Flowages, with a few differences. First, the relationships between CHL and TP and TN are weaker in Lake Wisconsin. Second, CHL reaches higher concentrations earlier in the season (around June 1) and follows less of a seasonal pattern than the other reservoirs. And third, the relationship between CHL and Q is clearer in Lake Wisconsin, and there is no evidence of less CHL at the lowest flows.

Modeling methods

While scatter plots can suggest which variables might be driving CHL production, statistical models can characterize the effect of one variable while controlling for others, and can characterize interactions among variables. Generalized Additive Models (GAMs) fit with the mgcv package in R were selected for this analysis because they allow simple specification of complex interactive non-linear relationships. The *te* function was used in the *gam* formulae to fit tensor product smooth functions between the predictor and response variables. This can be thought of as a surface in n (predictor) dimensional space where the value of the surface is estimated CHL concentration and the complexity of the surface is balanced against the fit to the data. There are 128-167 CHL observations per reservoir, so the number of variables in each model was limited to three, given that several degrees of freedom are used by non-linear and interactive effects. Initially, separate models were developed for Petenwell and Castle Rock, but these models were very similar, so a single model was developed for both of these reservoirs. Rather than test all possible combinations of variables, candidate models were constructed to compare plausible hypotheses about the drivers of CHL variability. All models included TP, and additional variables included TN, Q, and either JD or TEMP.

Model structure

The best model for Petenwell/Castle Rock, as assessed by Generalized Cross Validation score, included TP, Q, and JD (Model #1, Table 3). The relationships between these variables and CHL are best visualized through bivariate contour plots, which show estimated CHL across ranges of two variables, while holding the other variable constant at its median value. The contours were augmented with shading to help visualize the transition from low (blue) to high (green) CHL. In Petenwell/Castle Rock, CHL increases with TP and peaks at low to moderate Q (Figure 4). CHL is lower during April-June for a given TP than in late summer (Figure 5). Model #6 was used assess the potential influence of TN on CHL. The contour plot of TP and TN clearly shows that TN has almost no influence on CHL after controlling for the effect of TP (Figure 7).

The best model for Lake Wisconsin included TP and Q (Model #2, Table 4). Model #1 had a slightly lower GCV score, but the contour plots indicated some predictions outside of the range of observations that did not make sense, including negative correlations between CHL and TP at high Q and low JD (April-May). Based on Model #2, CHL increases with TP, especially at low Q (Figure 8). There is no evidence of a drop in CHL at very low Q, as seen with Petenwell/Castle Rock. Based on Model #3, there is no evidence that TN affects CHL after controlling for the effect of TP (Figure 9).

Model diagnostics

Model diagnostic plots were created for both the entire dataset for each reservoir, which includes data from late April to late September (Figures 10-12), and for the CHL assessment period (July 15 – September 15; Figures 13-15). The plots show that the models are more accurate and less biased during the CHL assessment period, which supports their use for SSC development.

Boxplots of model residuals (observed – model estimated CHL) by monitoring station show that there are some differences in CHL response to the model variables among stations. In particular, for Petenwell and Castle Rock, after controlling for TP, JD, and Q, CHL decreases moving downstream in Petenwell and increases from the upstream to the lower two stations in Castle Rock. Lake Wisconsin has a similar pattern to Castle Rock, where the upstream station has lower residuals than the other two stations. We explored including station ID as a categorical variable in the models, but it complicated application of the models to the reservoir-wide simulations described below.

Plots of residuals vs estimated CHL indicate increased variance at low CHL, especially in Petenwell. Empirical cumulative frequency distribution (ECDF) plots show that the models overestimate low CHL and underestimate high CHL in all three reservoirs across the entire monitoring season. The most accurate frequency estimates on these plots are where the observed and estimated lines overlap. For example, in Lake Wisconsin, the observed and estimated frequencies of CHL in the range of 20-50 µg/L are almost identical. The degree of agreement between the observed and estimated CHL frequencies is higher for the CHL assessment period, and importantly, all three reservoirs appear to have unbiased estimates of the frequency of CHL in the range of 20 µg/L to the 70^{th} percentile concentration, which is the range that will be expected to decrease below 20 µg/L under the SSC.

Model simulations

The CHL models were then used to simulate daily CHL concentrations across the monitoring seasons of 2010-13. TP concentrations on unmeasured days were estimated by linear interpolation between measured values. Plots of measured and simulated CHL are shown in Figures 16-18. The patterns of simulated CHL generally match the observed patterns well, including the seasonal trend, occasional sharp decreases due to high flow events, and interannual variability (lower peak CHL in 2012 in Petenwell and Castle Rock and slightly higher peak CHL in 2012 in Lake Wisconsin).

The CHL models were then paired with TP models for each reservoir to simulate CHL response to TP load reductions, and to determine the TP load and in-lake TP concentration that will meet the CHL target for recreational use.

In Petenwell and Castle Rock Flowages, the Jensen models described in Appendix G were used to simulate daily TP concentrations for each reservoir. As described in the Jensen model methods, the simulated TP concentrations for each reservoir represent the median across all stations. The Petenwell/Castle Rock CHL model was then used to simulate baseline CHL concentrations for each reservoir. Then, through trial and error, TP loading was reduced until the target for recreational use (70^{th} percentile CHL < 20 µg/L during July 15 – September 15) was met. Specifically, a uniform percent reduction was applied to each daily inflow TP concentration, including outside the CHL assessment period, which assumes that as overall loading decreases, the temporal pattern of TP loading will remain the same. Figures 19 and 20 show simulated time series of TP and CHL for both baseline and site-specific criterion scenarios for Petenwell and Castle Rock Flowages.

In Lake Wisconsin, the BATHTUB model described in Appendix H indicated that reservoir TP concentrations were equal to inflow concentrations. Therefore, simulating the effects of reduced TP loading simply entailed reducing each daily reservoir TP concentration by a uniform percentage until the target for recreational use (70^{th} percentile CHL < 20 µg/L during July 15 – September 15) was met. To make the assessment comparable to Petenwell/Castle Rock, baseline reservoir TP was estimated by calculating the median reservoir TP across the three monitoring stations on each sampling date, and then linearly interpolating between these values to estimate daily TP concentrations. Baseline CHL was then predicted from this reservoir-median daily TP dataset, along with measured daily discharge at the Prairie du Sac dam. As with Petenwell/Castle Rock, the TP reductions required to meet the CHL target in late summer in Lake Wisconsin were applied across the entire year. Figure 21 shows simulated time series of TP and CHL for both baseline and site-specific criterion scenarios for Lake Wisconsin.

Based on this analysis, the recommended SSC for Petenwell and Castle Rock are 53 and 55 µg/L TP, respectively, as a summer (June 1 – September 15) mean concentration, which is higher than the existing criteria (40 µg/L TP). The recommended SSC for Lake Wisconsin is 47 µg/L TP, which is lower than the existing criterion (100 µg/L TP).

Discussion

The empirical models described in this report estimate the TP concentrations that are expected to meet the chlorophyll *a* (CHL) target for recreational use (70^{th} percentile CHL < 20 µg/L during July 15 – September 15) in Petenwell and Castle Rock Flowages and Lake Wisconsin. These models are based on four years of biweekly monitoring data. The models indicate that variation in CHL in these reservoirs is primarily driven by total phosphorus, but that river discharge and seasonal variation also play a role. High river discharge probably reduces CHL because it flushes algae through more quickly and is associated with turbid water that reduces light availability for algal growth. The seasonal pattern observed in Petenwell and Castle Rock Flowages (after controlling for TP and Q) is probably related to variation in solar radiation and possibly algal grazing by zooplankton in May-June (which is a common period of clear water in many lakes), and possibly algal taxonomic succession, where taxa with low chlorophyll density dominate in May-June, and taxa with high chlorophyll density dominate in July-August. The lack of influence on nitrogen on CHL variation suggests that it rarely limits algal growth in these reservoirs. This is somewhat surprising, given that inorganic nitrogen (the form available for algal uptake) dropped to undetectable levels several times during the late summers of 2010-13 in in Petenwell and Castle Rock Flowages. One possible explanation for this phenomenon is that algal taxa that can fix atmospheric nitrogen (e.g., cyanobacteria) became dominant during these conditions, and kept CHL production high.

Comparison of the two reservoir models indicates that Lake Wisconsin produces more CHL per unit TP than Petenwell and Castle Rock Flowages, particularly during low flow conditions. For example, at the lowest flows observed during 2010-13 (1,000-1,500 cfs in Petenwell/Castle Rock and 2,000-3,000 cfs in Lake Wisconsin), the Lake Wisconsin model estimates that an increase in TP from 60 to 120 µg/L would increase CHL from about 30 to 90 µg/L, while this same TP range in Petenwell/Castle Rock would only increase CHL from about 20 to 30 µg/L. This difference can also be seen in the data plots of the dry summer of 2012, where Petenwell/Castle Rock had the lowest CHL of the four-year period, and Lake Wisconsin had the highest CHL (Figures 16-18). The lower sensitivity to TP in Petenwell/Castle Rock at low flows is the reason that the recommended SSCs are higher for these reservoirs.

Figure 22 provides another way to visualize the predicted sensitivity of CHL to TP in these reservoirs, and to put it in context of assessments of other lakes and reservoirs. There are four reservoirs on the Wisconsin River or its tributaries upstream of Petenwell Flowage that have been assessed for TP and CHL. The predicted SSC CHL/TP ratios of Petenwell, Castle Rock, and Lake Wisconsin are within the range of values in these upstream reservoirs. It is unclear what causes the large range in CHL/TP ratios among these reservoirs – from 0.21 in Spirit River Flowage to 0.52 in Lake Mohawksin. The predicted response of CHL to TP reductions in Petenwell, Castle Rock, and Lake Wisconsin is similar to the overall CHL/TP relationship among all Wisconsin lakes and reservoirs (gray line in Figure 22). The response of CHL to TP reductions is steeper in Lake Wisconsin than the other two reservoirs, but the CHL/TP ratio in Lake Wisconsin in the SSC scenario is still projected to be higher than the other two reservoirs.

Ultimately, the SSC estimated by this analysis are predictions outside of the range of observed conditions (i.e., extrapolation). The accuracy of extrapolated relationships is always less certain than when the projected condition is within the range of observations (i.e., interpolation). In this situation, the risk of significant errors can be mitigated by evaluating alternative models, by comparing the estimated relationships with theoretical expectations, and by comparing the projections with other water bodies that are already in the range of the projections. If the SSC for TP are met, but CHL is still exceeding targets, new TP SSC may be estimated and adopted.

Table 1. Monitoring stations on Petenwell and Castle Rock Flowages and Lake Wisconsin.

Station ID	Description
10031168	Petenwell - 10.4 miles upstream of dam
10031169	Petenwell - 7.8 miles upstream of dam
10031170	Petenwell - 4.7 miles upstream of dam
10031171	Petenwell - 1.8 miles upstream of dam
10031172	Castle Rock - 7.7 miles upstream of dam
10031173	Castle Rock - 3.7 miles upstream of dam
10031174	Castle Rock - 1 mile upstream of dam
10031184	Lake Wisconsin - Between Stoners Bay and Pine Bluff
10031185	Lake Wisconsin - Upper reach of reservoir
10031186	Lake Wisconsin - SW of Weigands Bay

Table 2. Water quality and hydrologic parameters

Abbreviation	Name	Units
CHL	Chlorophyll *a*	µg/L
JD	Julian day	day
Q	River discharge[2]	ft^3/s
TEMP	Water temperature	C
DO	Dissolved oxygen	mg/L
DOC	Dissolved organic carbon	mg/L
TN	Total nitrogen	mg/L
DIN	Dissolved inorganic nitrogen	mg/L
TKN	Total Kjeldahl nitrogen	mg/L
NO3	Nitrate + nitrite	mg/L
NH4	Ammonium	mg/L
TP	Total phosphorus	µg/L

[2] River discharge at the Petenwell Hydro Dam was used for Petenwell and Castle Rock Flowages. River discharge at USGS station ID 05406000 (Wisconsin River at Prairie du Sac) was used for Lake Wisconsin.

PO4	Ortho-phosphate	µg/L

Table 3. Candidate models for Petenwell/Castle Rock Flowages. Model formula conventions are specific to the gam function in the R package mgcv. GCV is the Generalized Cross Validation score (lower is better).

Model #	Formula	GCV
1	log(CHLA) ~ te(log(TP), log(Q), JD)	0.722
2	log(CHLA) ~ te(log(TP), log(Q), TEMP)	0.783
3	log(CHLA) ~ te(log(TP), JD)	0.798
4	log(CHLA) ~ te(log(TP), TEMP)	0.850
5	log(CHLA) ~ te(log(TP), Q)	0.878
6	log(CHLA) ~ te(log(TP), log(TN), log(Q), k=3.5)	0.882
7	log(CHLA) ~ s(log(TP))	0.967

Table 4. Candidate models for Lake Wisconsin. Model formula conventions are specific to the gam function in the R package mgcv. GCV is the Generalized Cross Validation score (lower is better).

Model #	Formula	GCV
1	log(CHLA) ~ te(log(TP), log(Q), JD, k=3)	0.223
2	log(CHLA) ~ te(log(TP), log(Q), k=4)	0.239
3	log(CHLA) ~ te(log(TP), log(TN), log(Q), k=4)	0.254
4	log(CHLA) ~ te(log(TP), TEMP)	0.315
5	log(CHLA) ~ te(log(TP), JD)	0.392
6	log(CHLA) ~ s(log(TP))	0.453

Figure 1. Scatter plots of chlorophyll a versus other parameters in Petenwell Flowage, 2010-13.

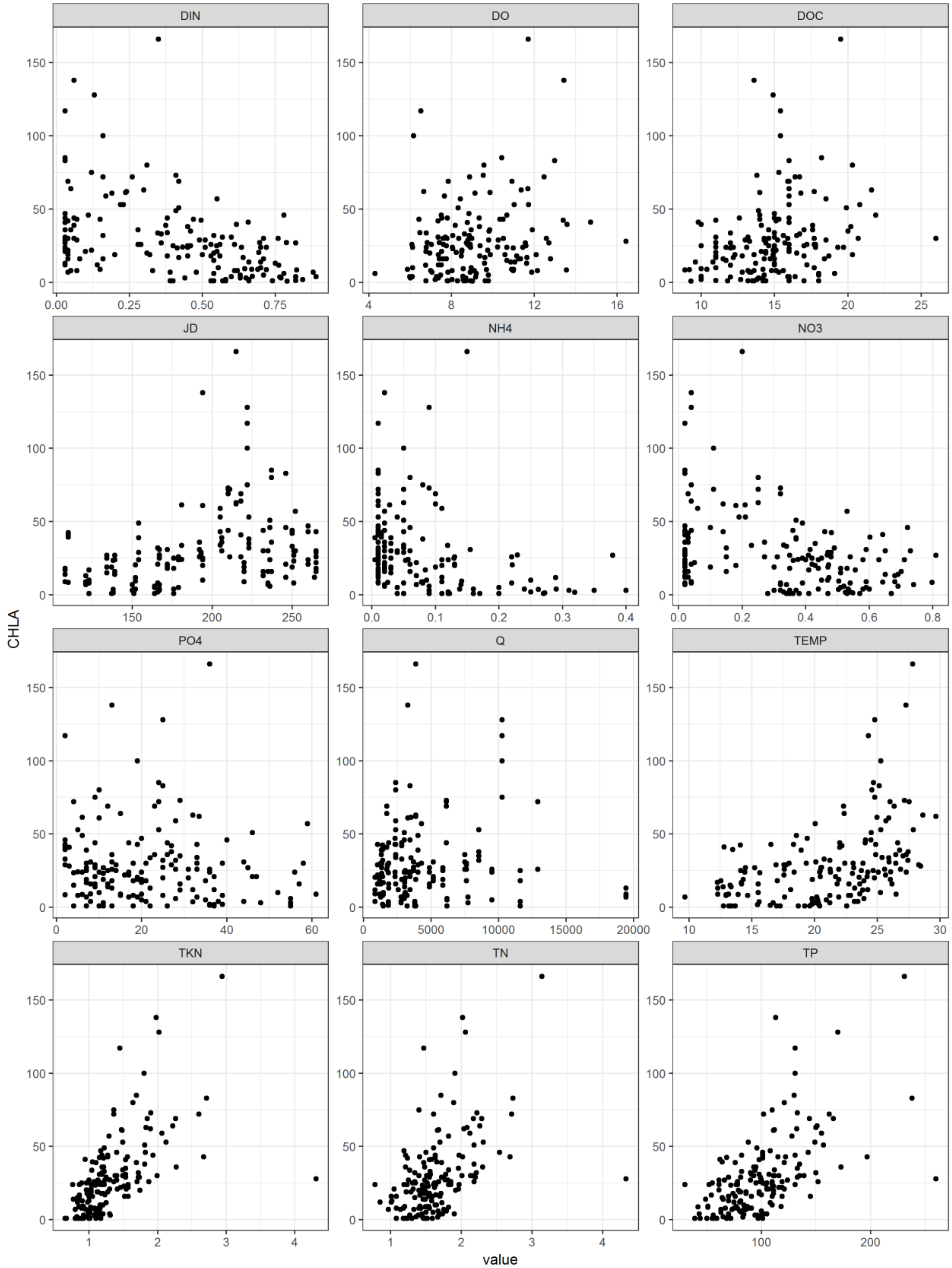

Figure 2. Scatter plots of chlorophyll a versus other parameters in Castle Rock Flowage, 2010-13.

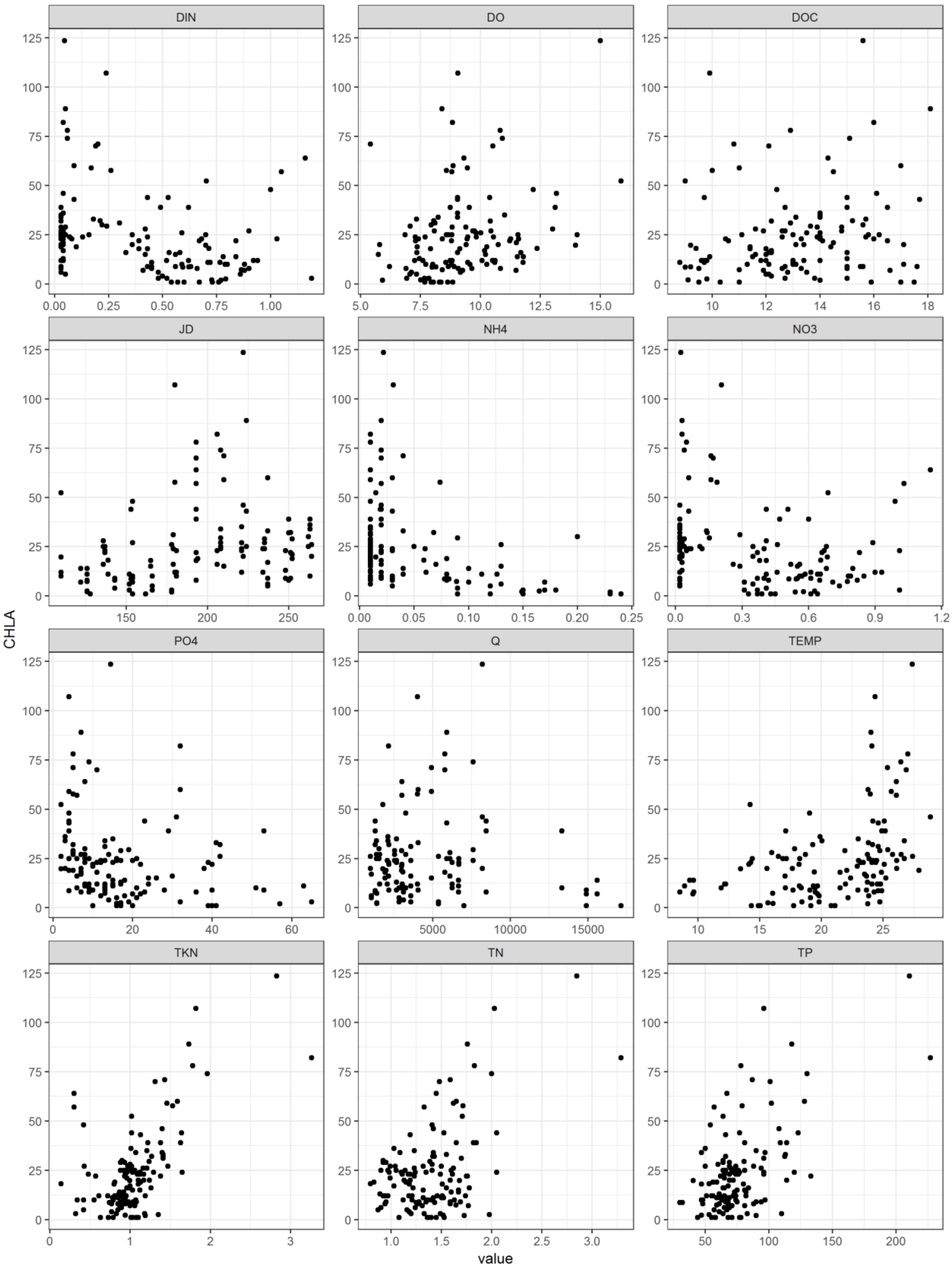

Figure 3. Scatter plots of chlorophyll a versus other parameters in Lake Wisconsin, 2010-13.

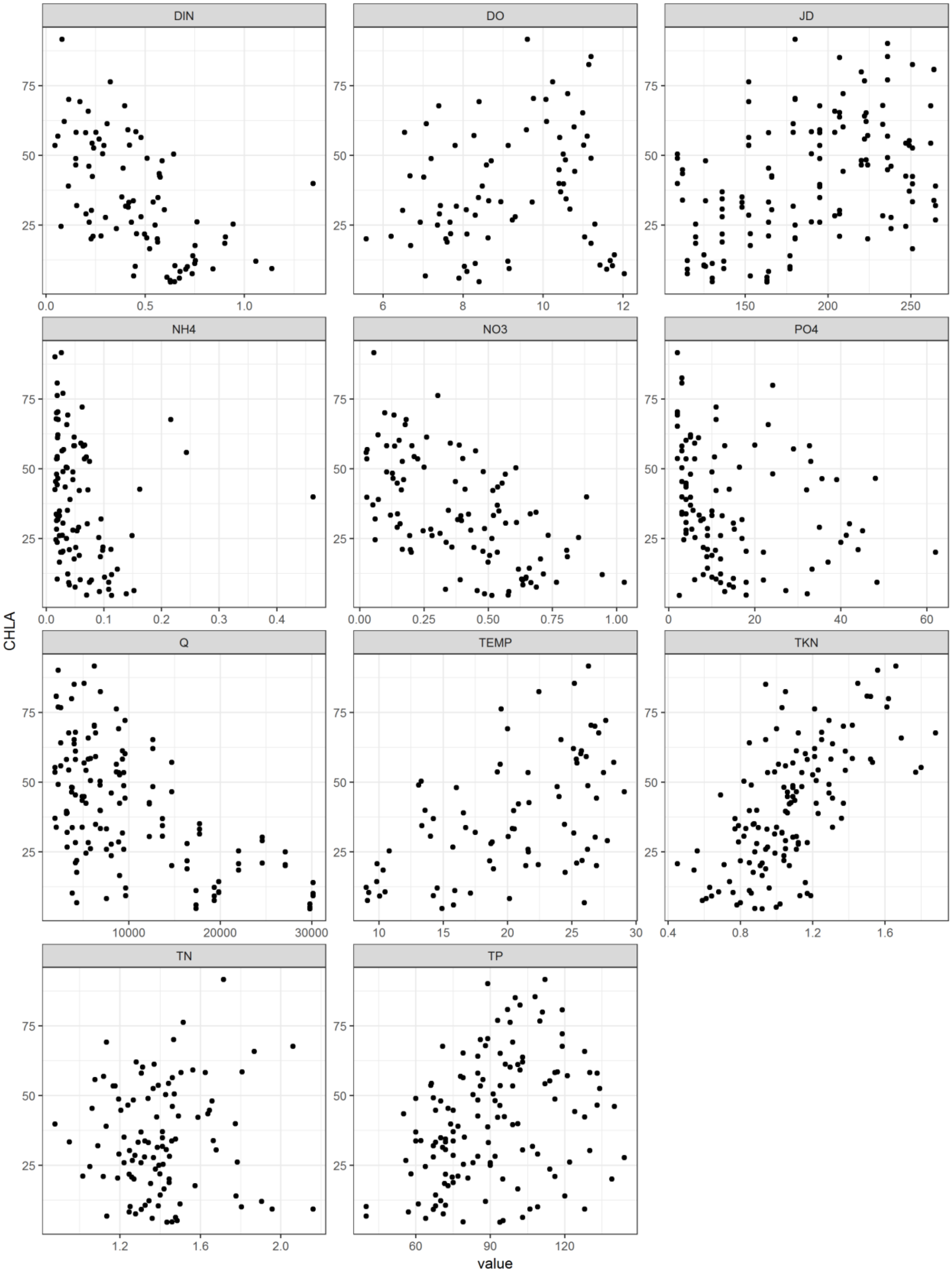

Figure 4. Contour plot of estimated CHL concentration (µg/L) as a function of TP (µg/L) and Q (cfs) in Petenwell/Castle Rock Flowages from Model #1 (Table 3). Circles are observations (diameter proportional to log(CHL) concentration).

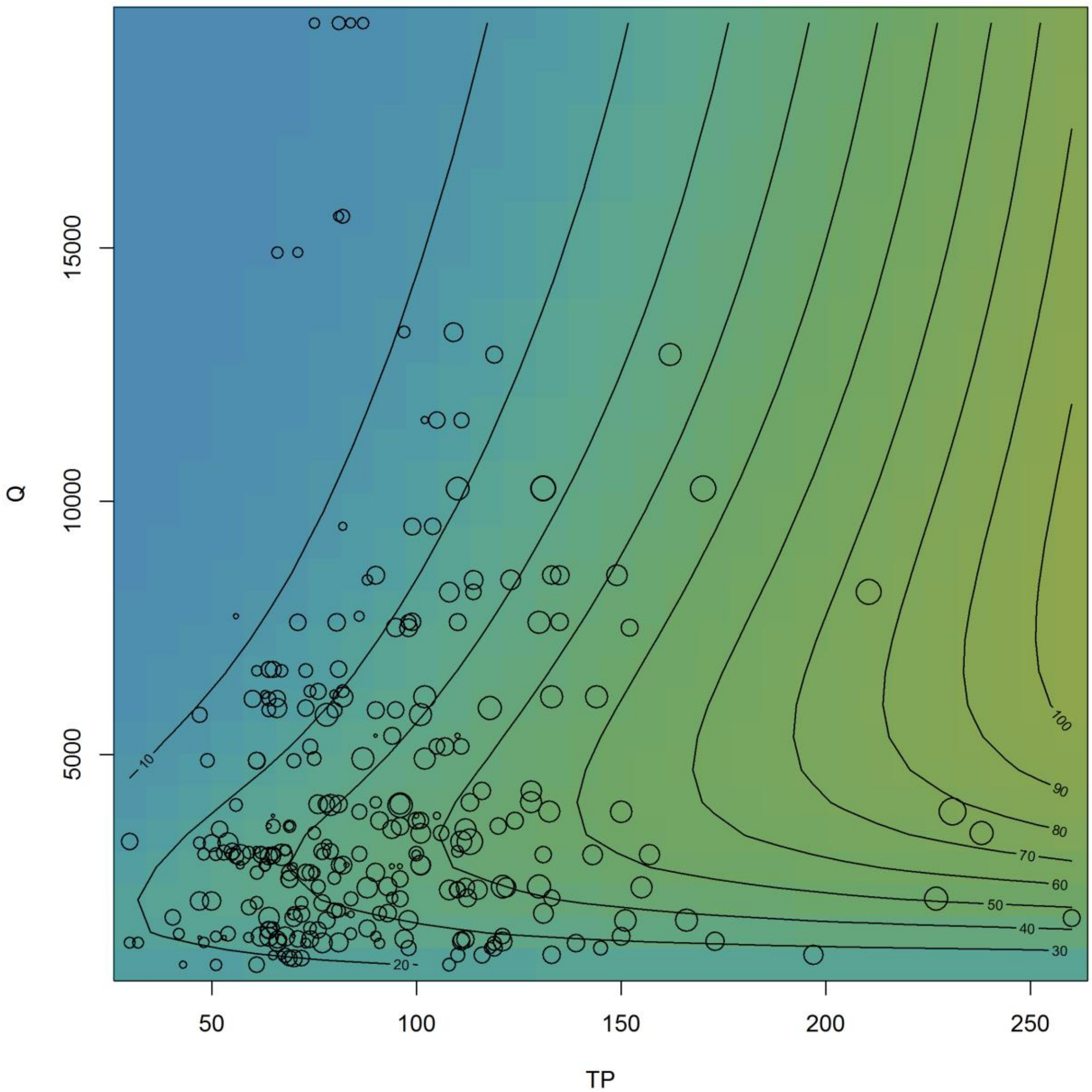

Figure 5. Contour plot of estimated CHL concentration (µg/L) as a function of TP (µg/L) and JD in Petenwell/Castle Rock Flowages from Model #1 (Table 3). Circles are observations (diameter proportional to log(CHL) concentration).

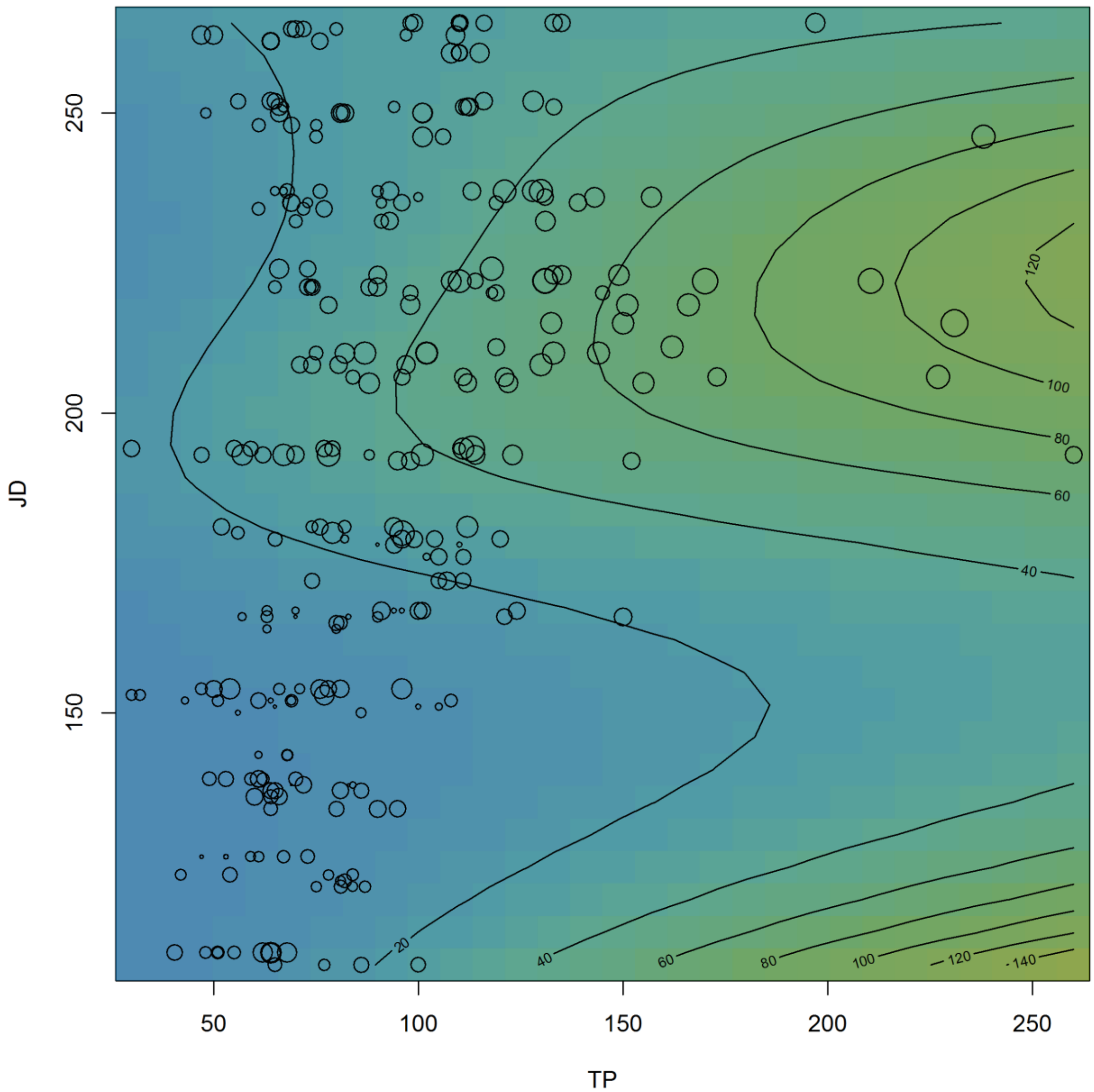

Figure 6. Contour plot of estimated CHL concentration (µg/L) as a function of Q (cfs) and JD in Petenwell/Castle Rock Flowages from Model #1 (Table 3). Circles are observations (diameter proportional to log(CHL) concentration).

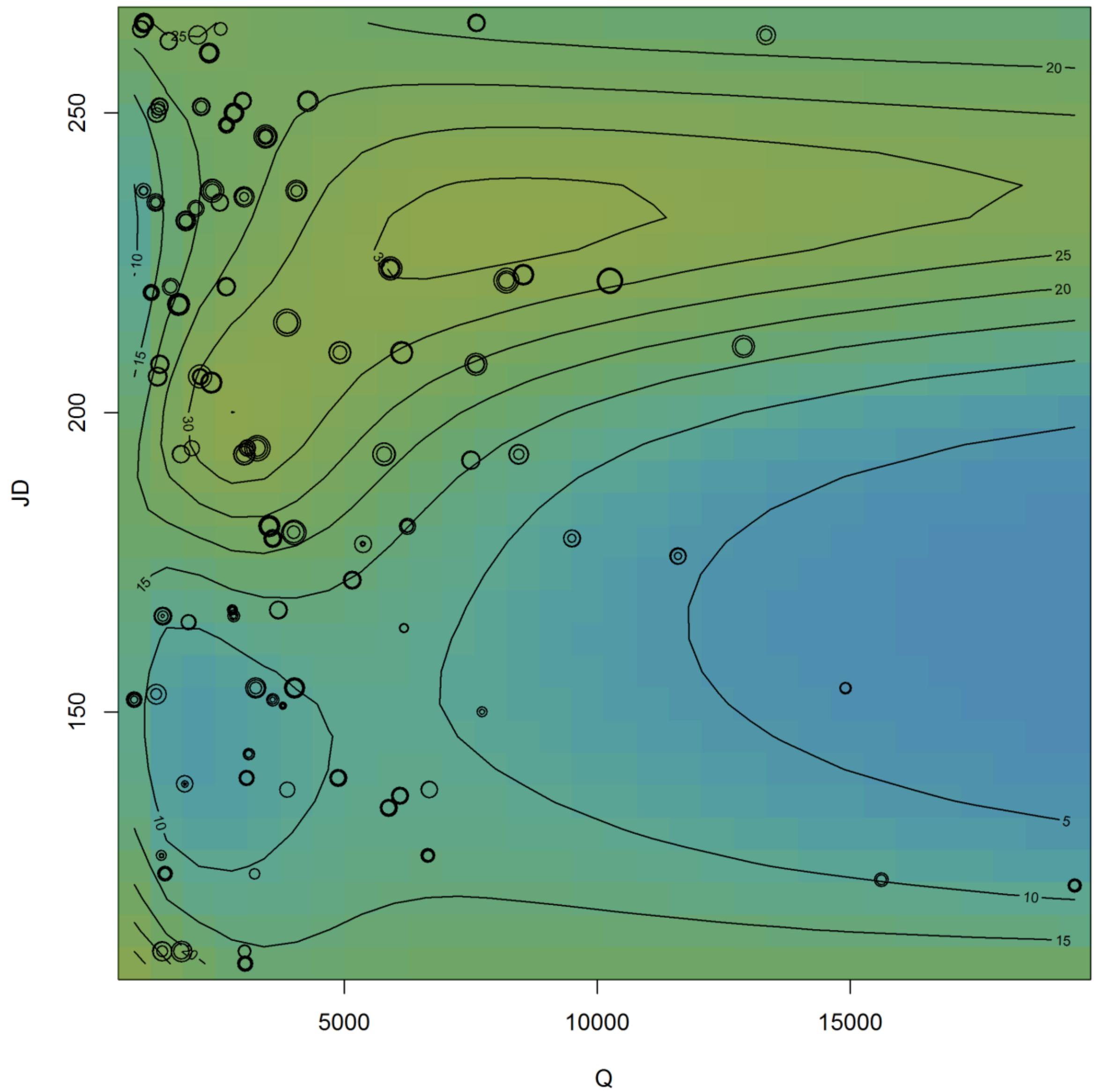

Figure 7. Contour plot of estimated CHL concentration (µg/L) as a function of TP (µg/L) and TN (mg/L) in Petenwell/Castle Rock Flowages from Model #6 (Table 3). Circles are observations (diameter proportional to log(CHL) concentration).

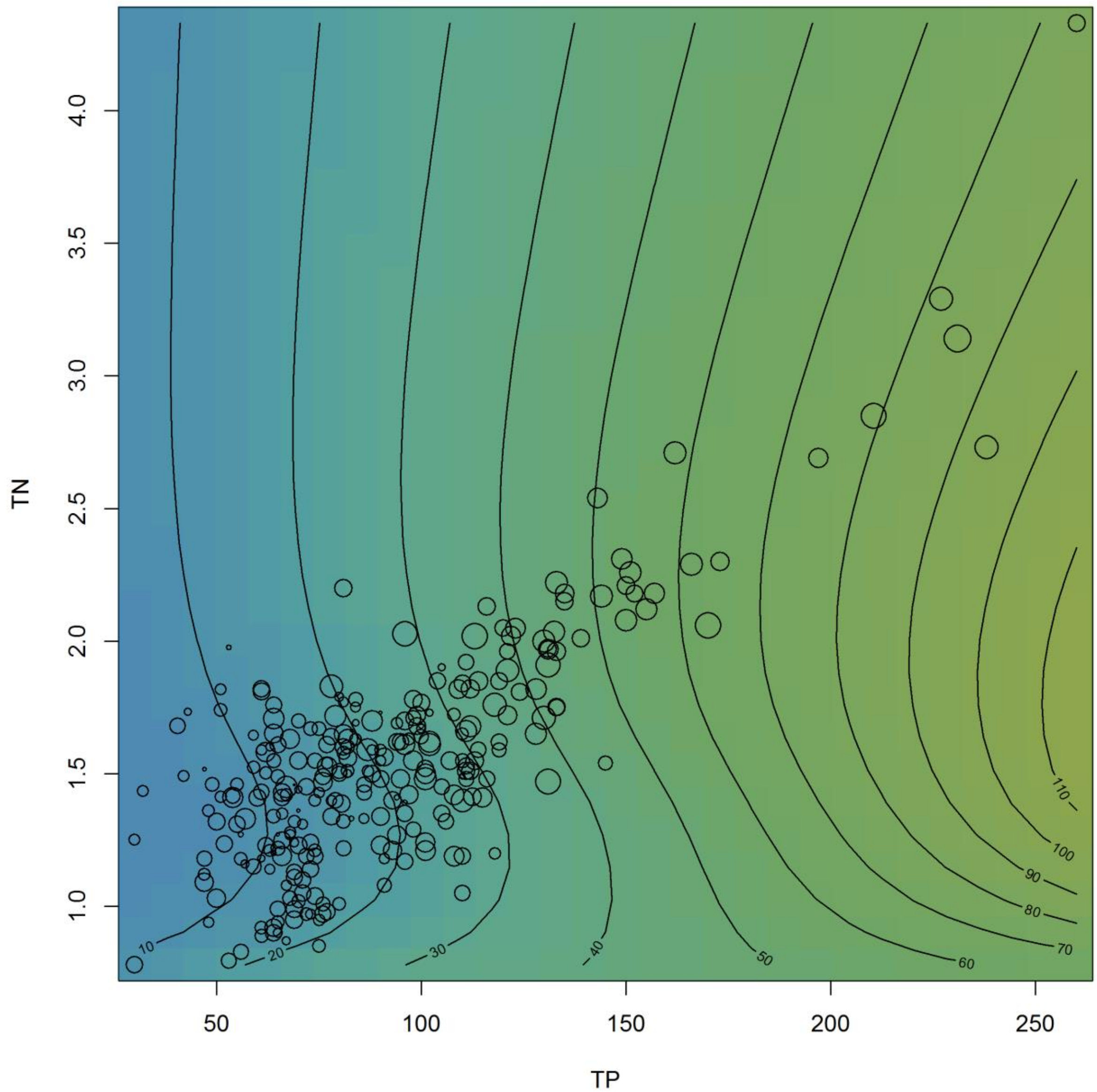

Figure 8. Contour plot of estimated CHL concentration (µg/L) as a function of TP (µg/L) and Q (cfs) in Lake Wisconsin from Model #2 (Table 4). Circles are observations (diameter proportional to log(CHL) concentration).

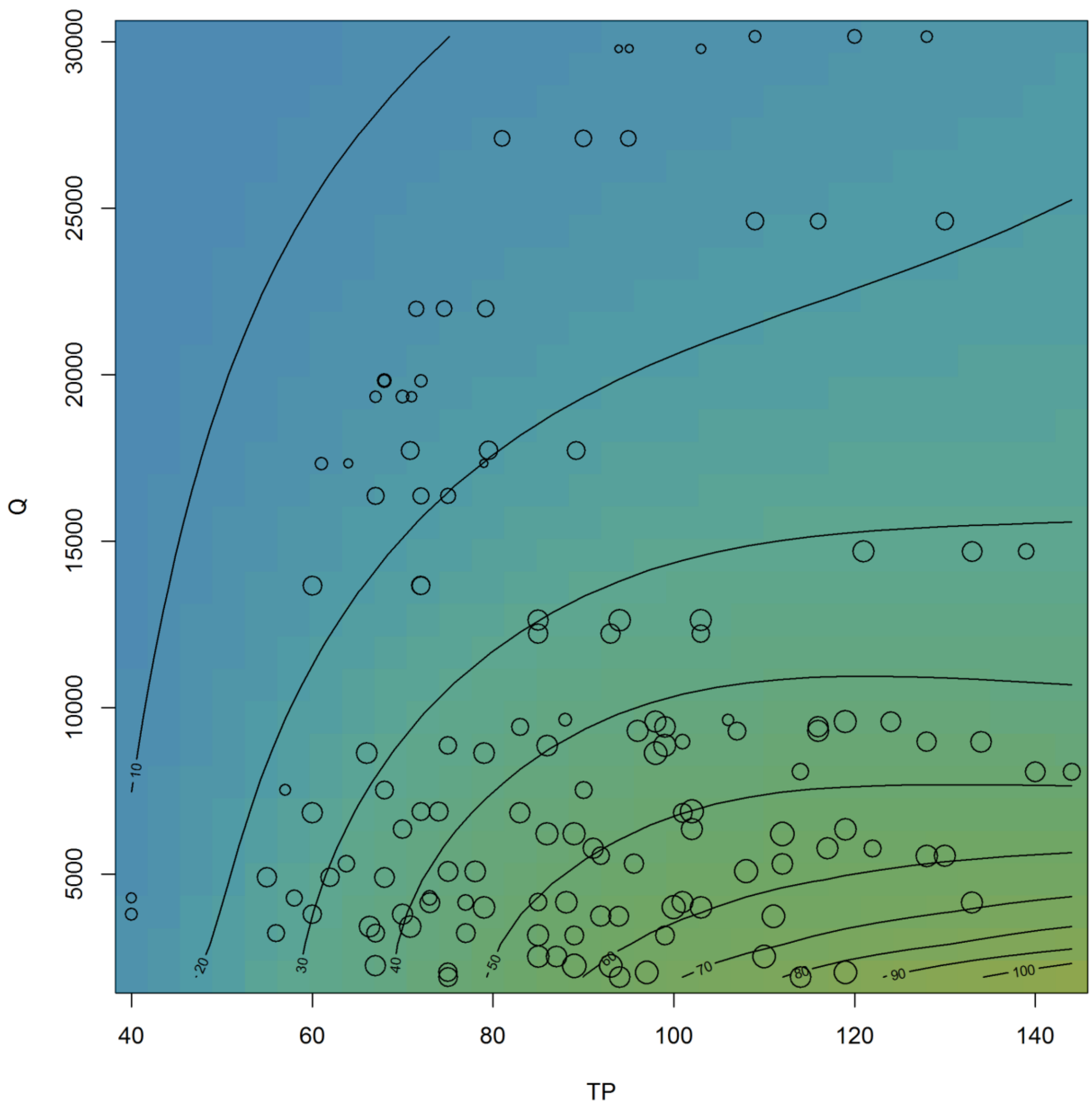

Figure 9. Contour plot of estimated CHL concentration (µg/L) as a function of TP (µg/L) and TN (mg/L) in Lake Wisconsin from Model #3 (Table 4). Circles are observations (diameter proportional to log(CHL) concentration).

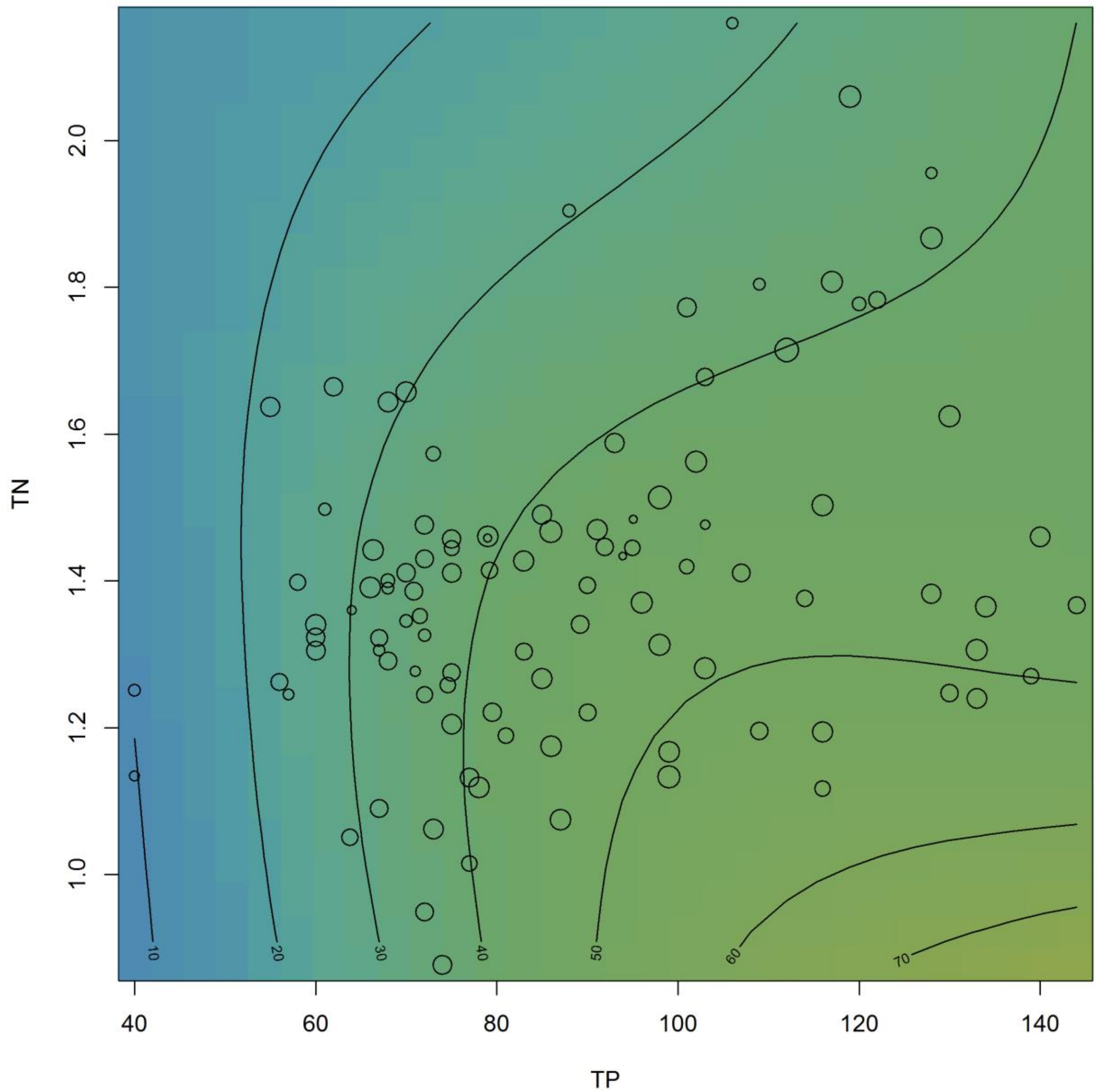

Figure 10. Model diagnostic plots for Petenwell Flowage CHL model.

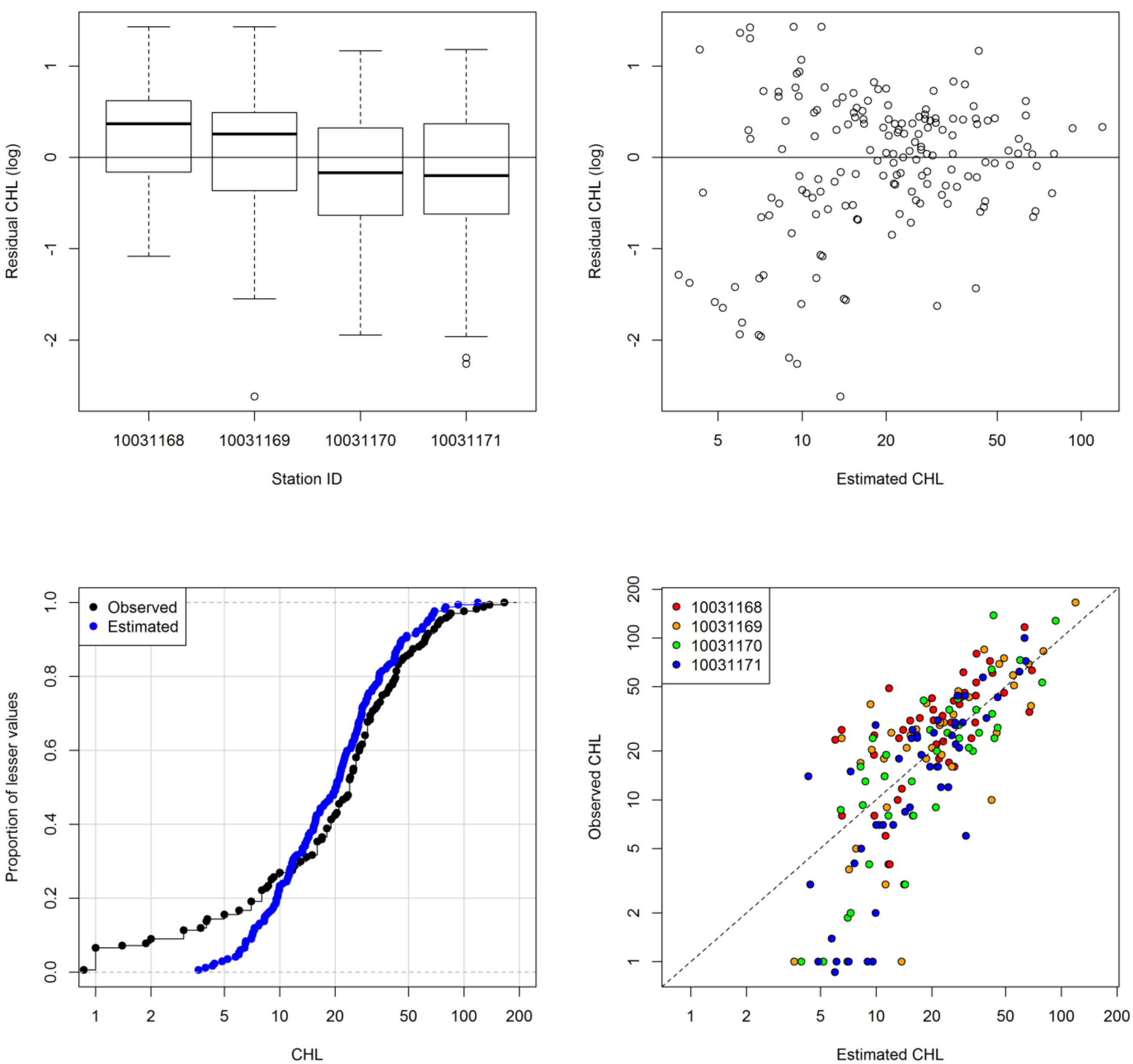

Figure 11. Model diagnostic plots for Castle Rock Flowage CHL model.

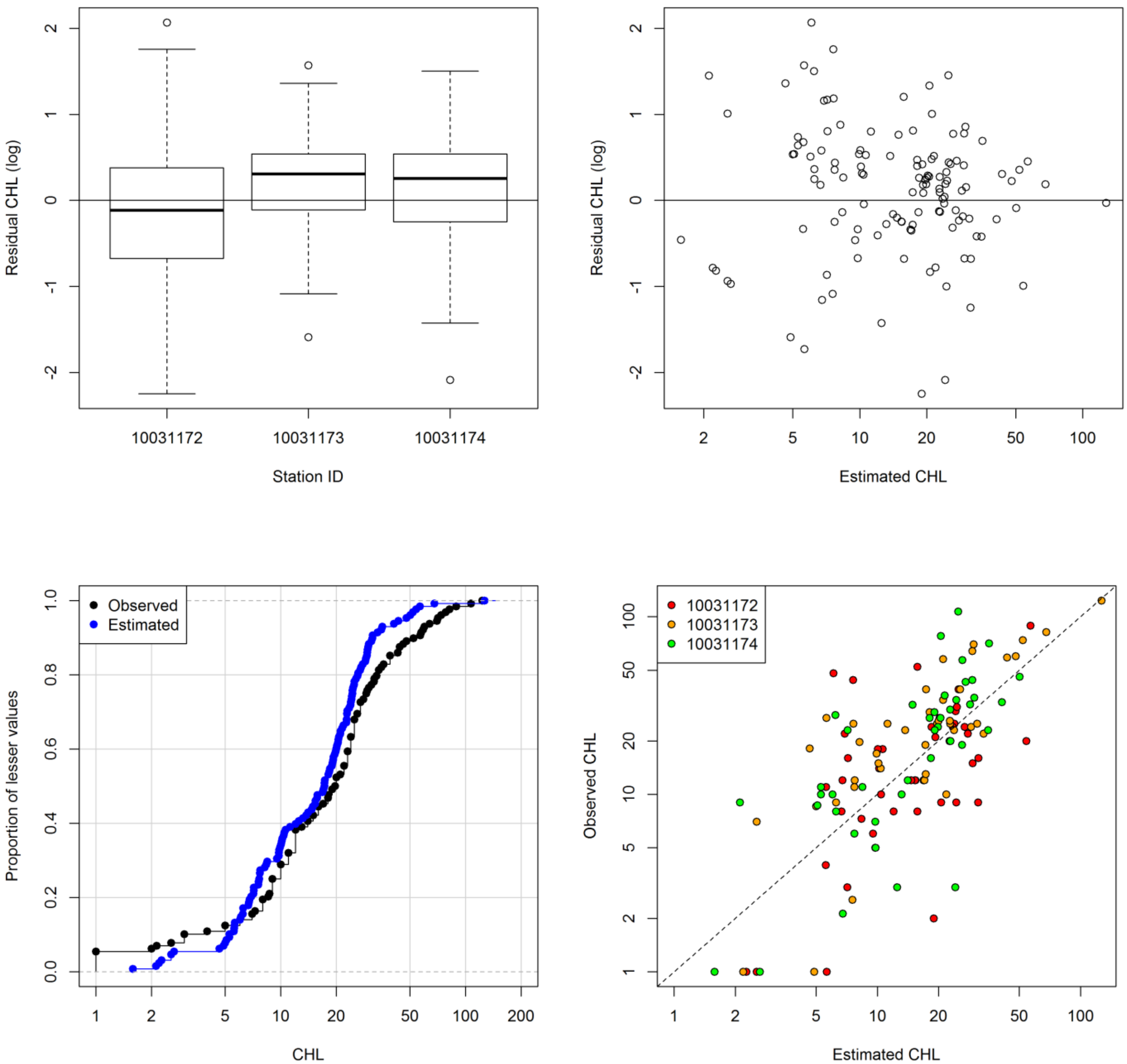

Figure 12. Model diagnostic plots for Lake Wisconsin CHL model.

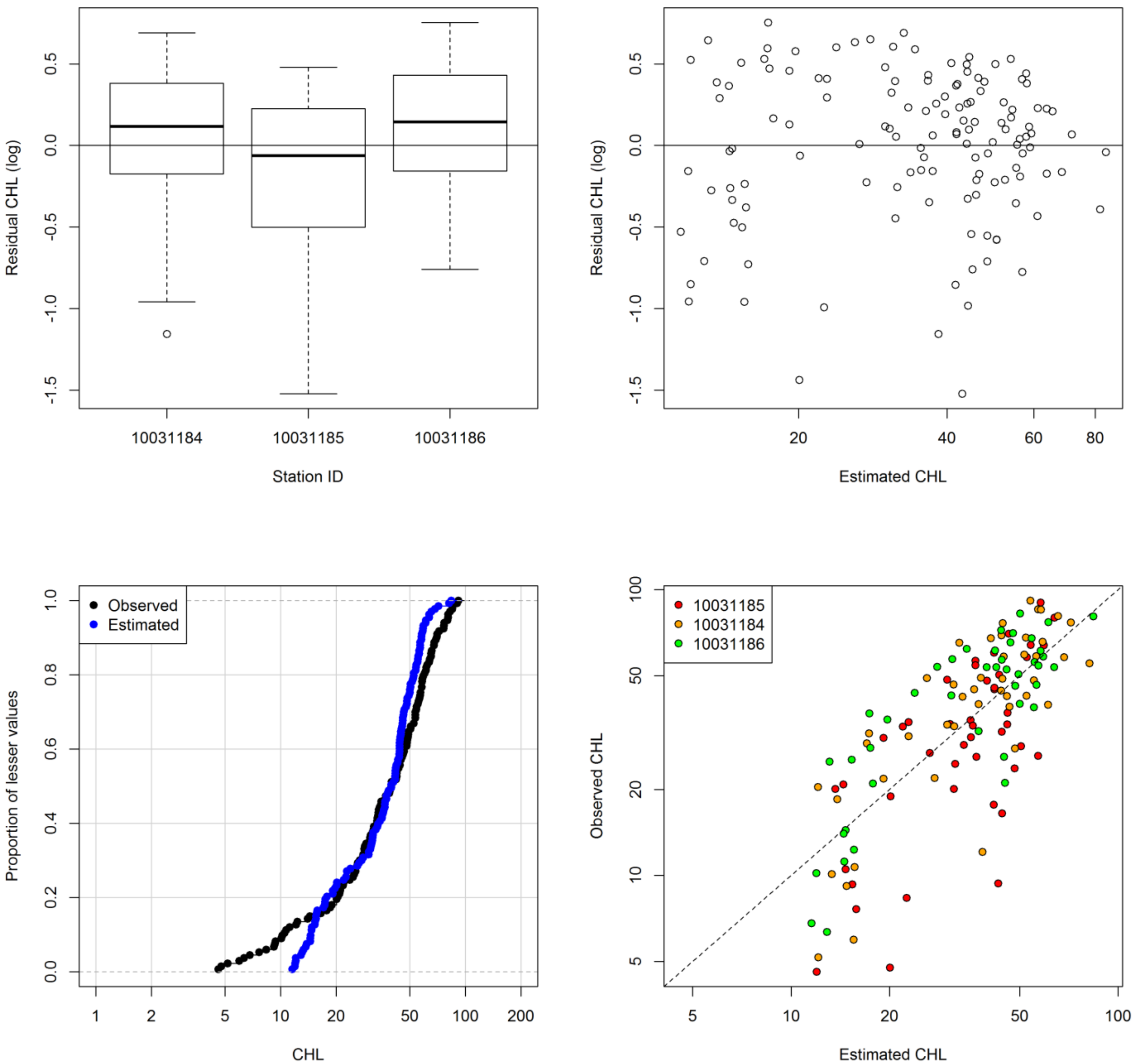

Figure 13. Model diagnostic plots for Petenwell Flowage CHL model (CHL assessment period: July 15 – September 15).

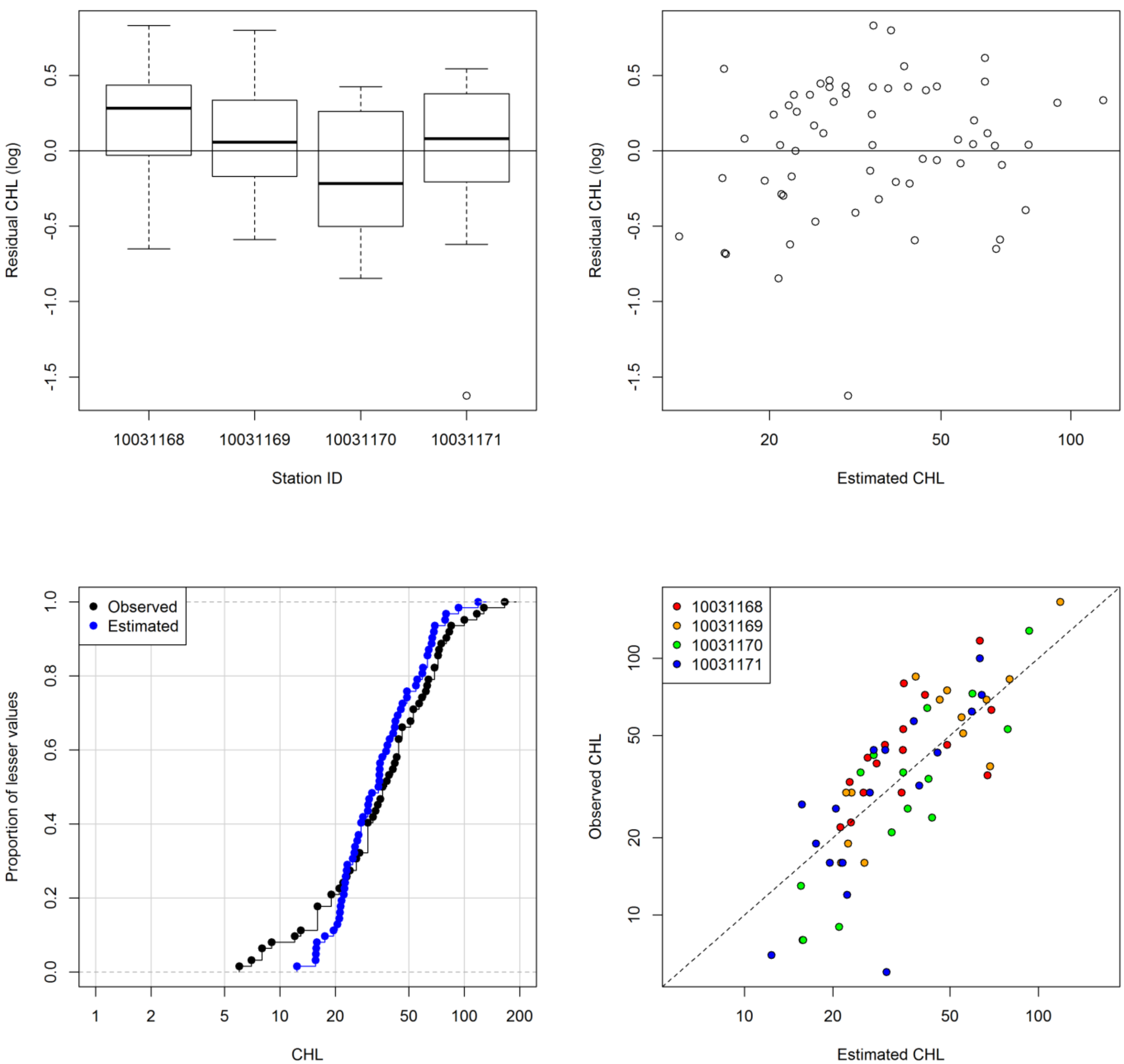

Figure 14. Model diagnostic plots for Castle Rock Flowage CHL model (CHL assessment period: July 15 – September 15).

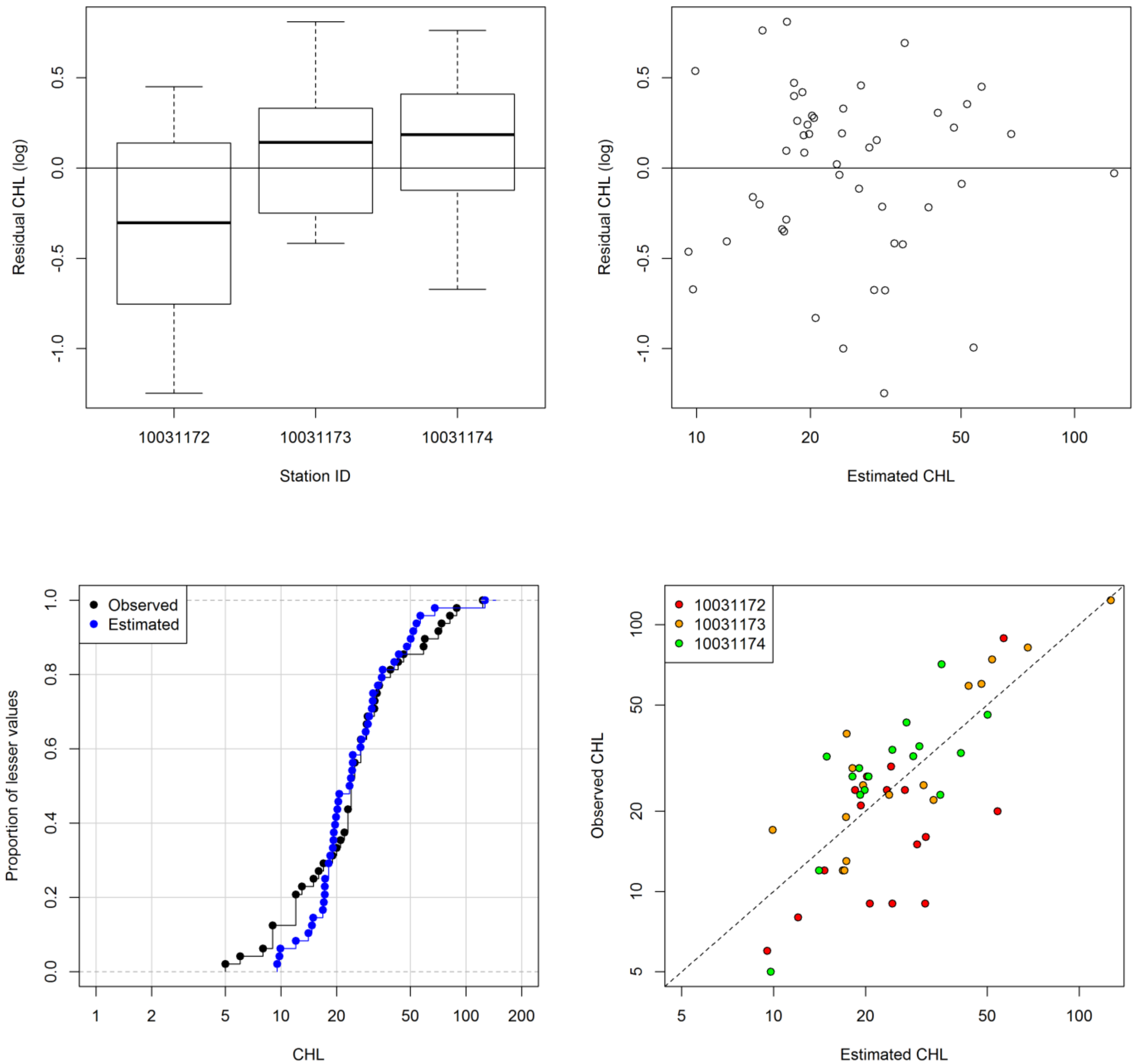

Figure 15. Model diagnostic plots for Lake Wisconsin CHL model (CHL assessment period: July 15 – September 15).

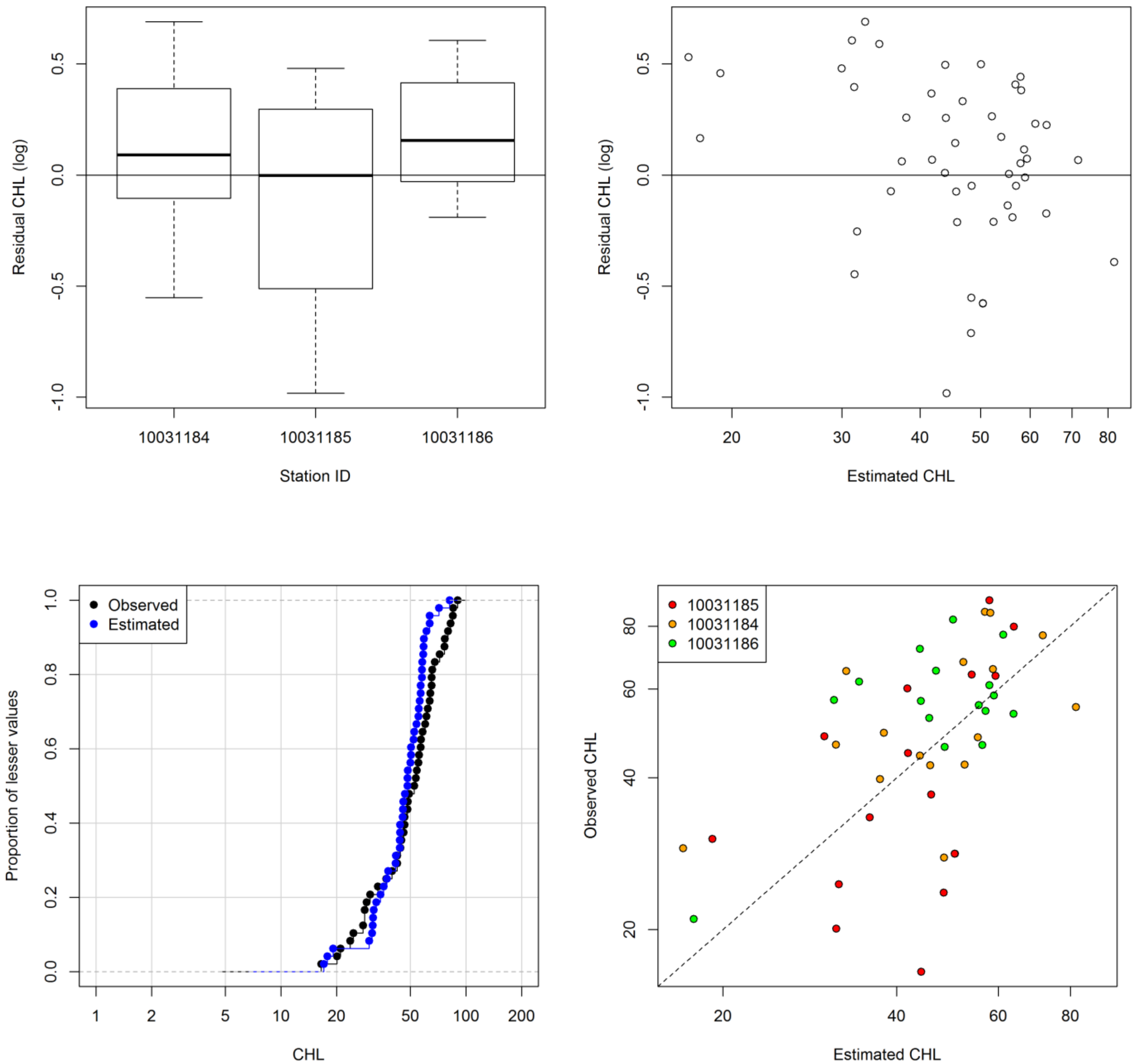

Figure 16. Observed (circles) and simulated (lines) chlorophyll *a* (µg/L) in Petenwell Flowage. Dashed line is recreational chlorophyll *a* target (20 µg/L). Shaded areas are chlorophyll *a* assessment periods.

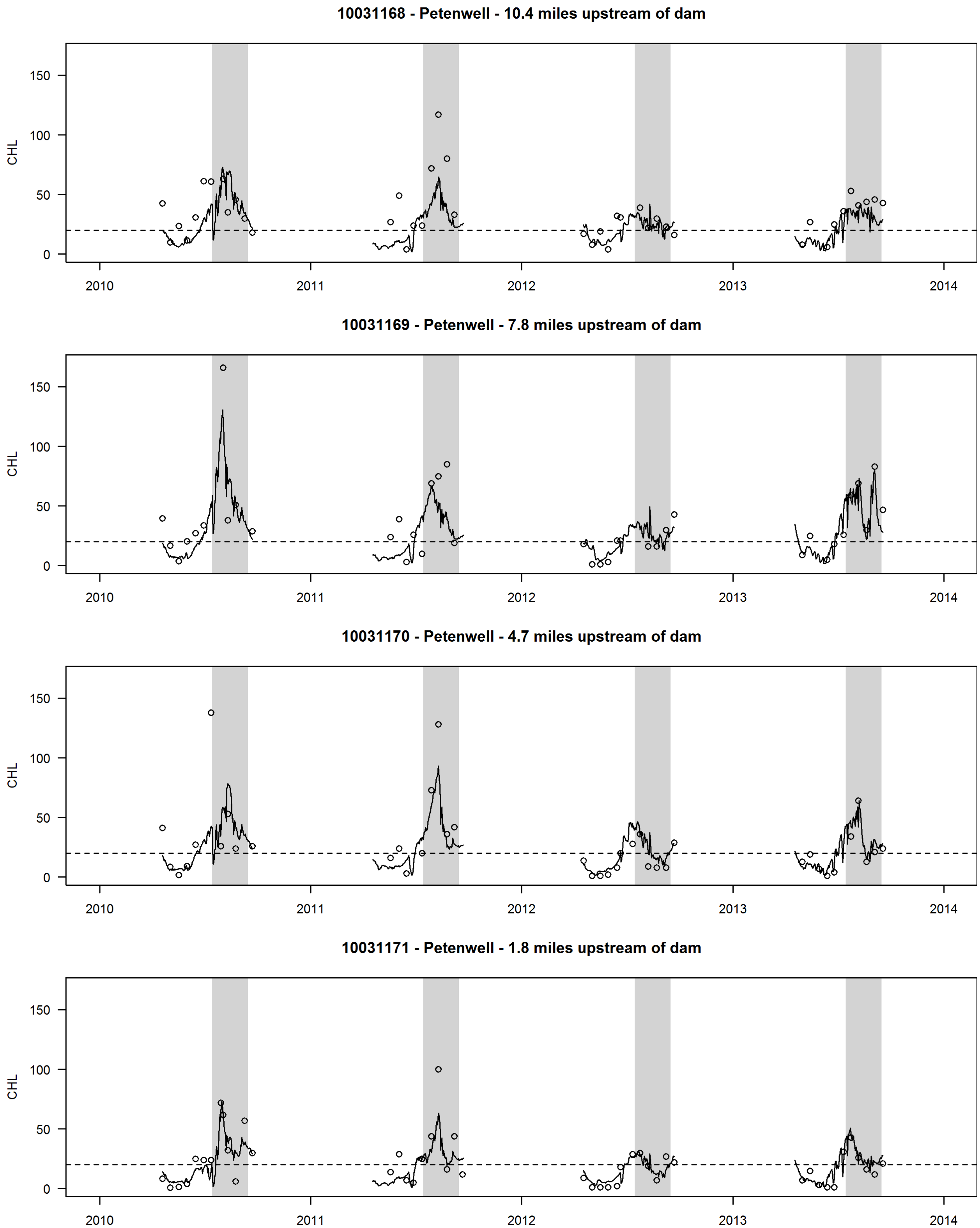

Figure 17. Observed (circles) and simulated (lines) chlorophyll *a* (µg/L) in Castle Rock Flowage. Dashed line is recreational chlorophyll *a* target (20 µg/L). Shaded areas are chlorophyll *a* assessment periods.

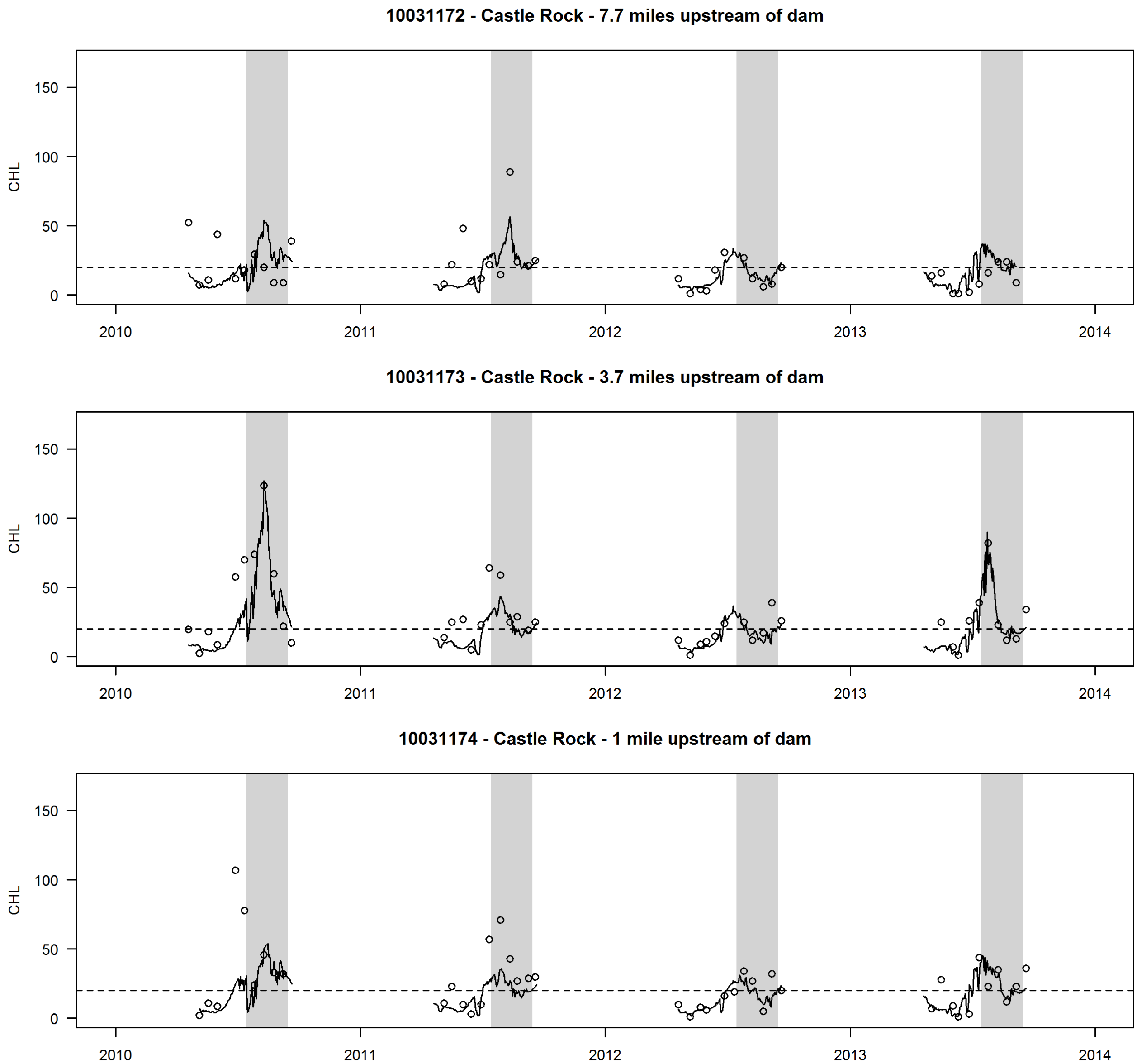

Figure 18. Observed (circles) and simulated (lines) chlorophyll *a* (µg/L) in Lake Wisconsin. Dashed line is recreational chlorophyll *a* target (20 µg/L). Shaded areas are chlorophyll *a* assessment periods.

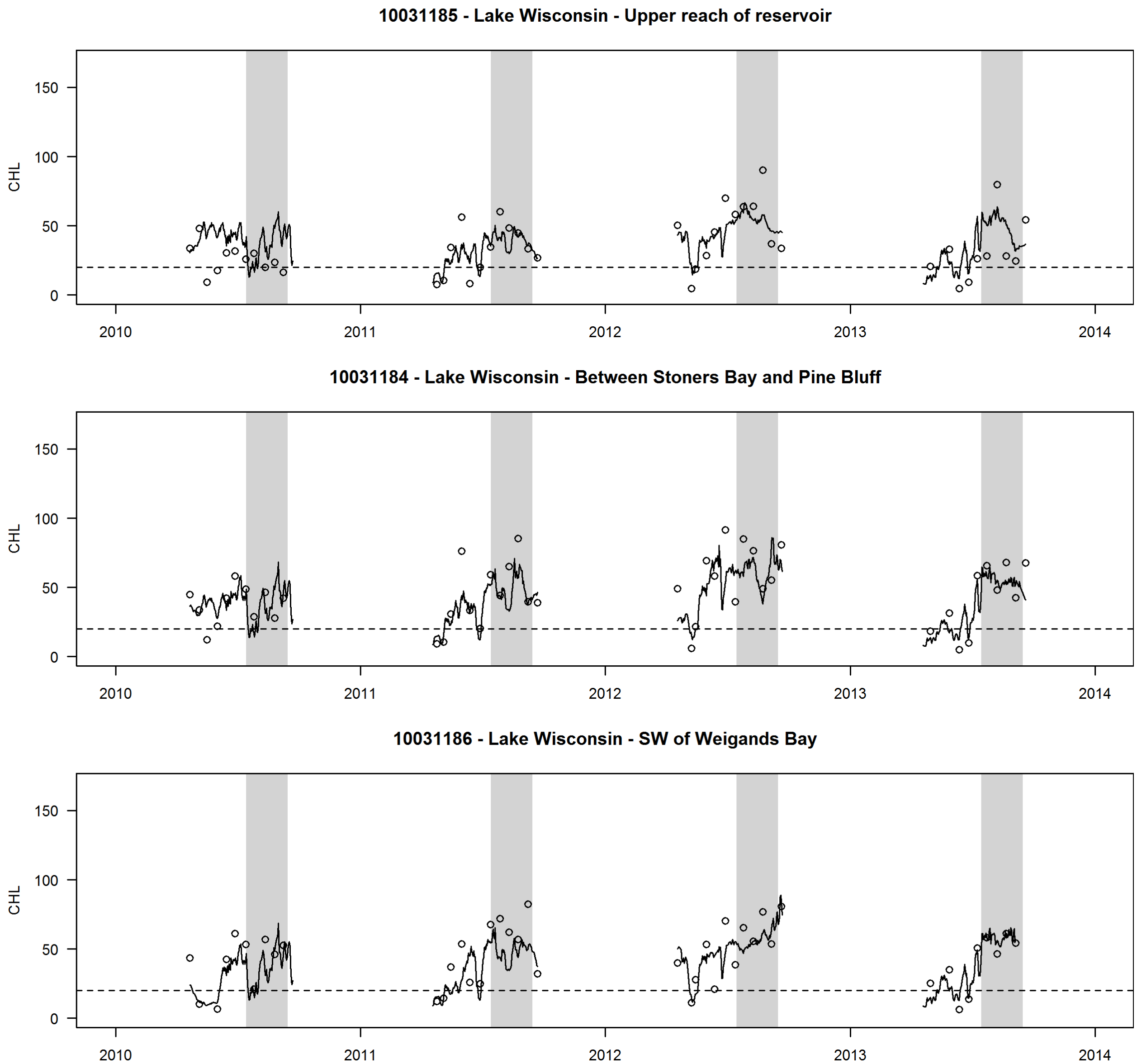

Figure 19. Baseline (black) and site-specific criterion (red) scenarios for total phosphorus (TP; µg/L) and chlorophyll *a* (CHL; µg/L) in Petenwell Flowage. Dashed lines are recommended TP site-specific criteria (53 µg/L) and recreational chlorophyll *a* target (20 µg/L). Shaded areas are assessment periods for each parameter.

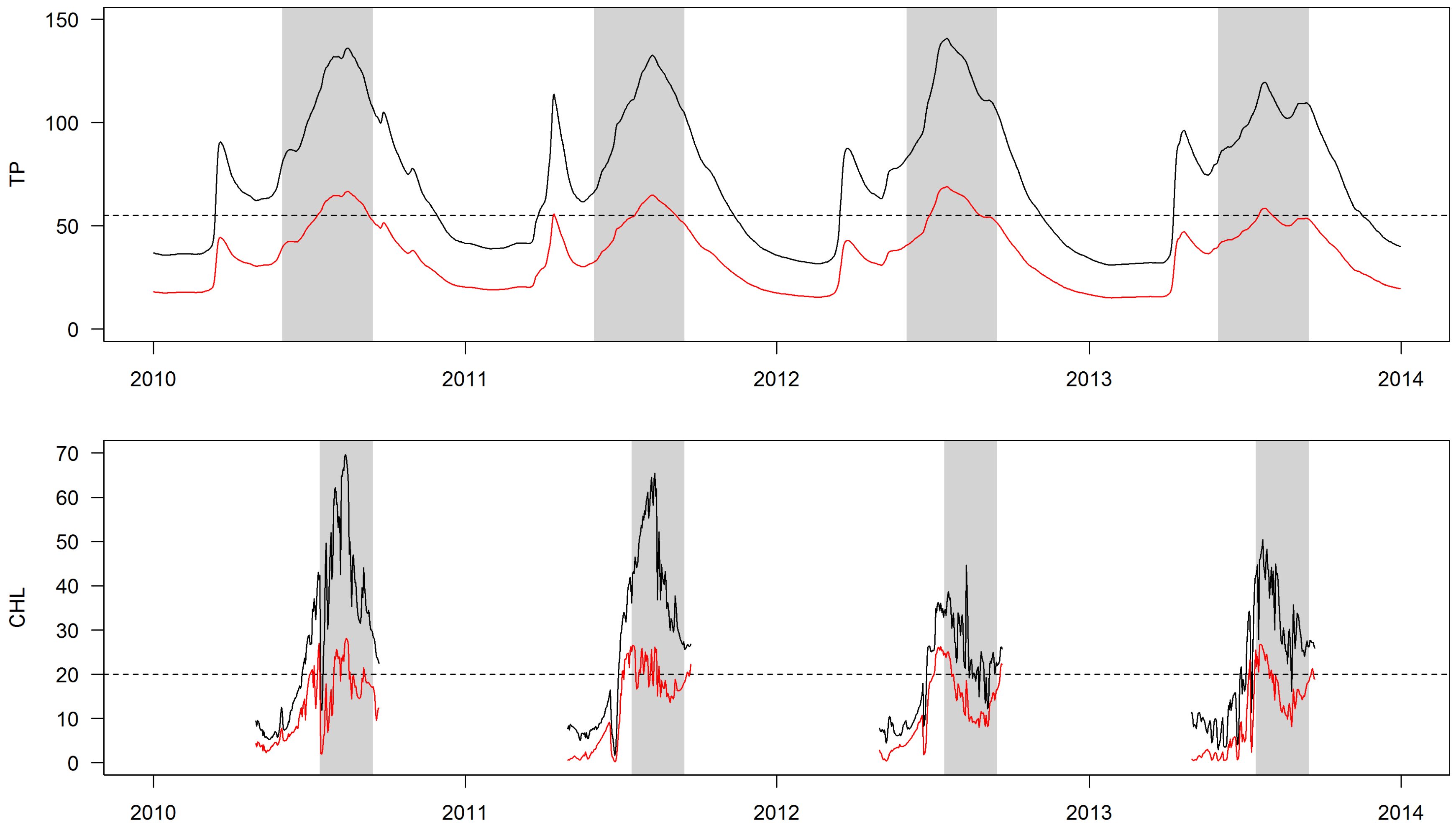

Figure 20. Baseline (black) and site-specific criterion (red) scenarios for total phosphorus (TP; µg/L) and chlorophyll *a* (CHL; µg/L) in Castle Rock Flowage. Dashed lines are recommended TP site-specific criteria (55 µg/L) and recreational chlorophyll *a* target (20 µg/L). Shaded areas are assessment periods for each parameter.

Figure 21. Baseline (black) and site-specific criterion (red) for total phosphorus (TP; µg/L) and chlorophyll *a* (CHL; µg/L) in Lake Wisconsin. Dashed lines are recommended TP site-specific criteria (47 µg/L) and recreational chlorophyll *a* target (20 µg/L). Shaded areas are assessment periods for each parameter.

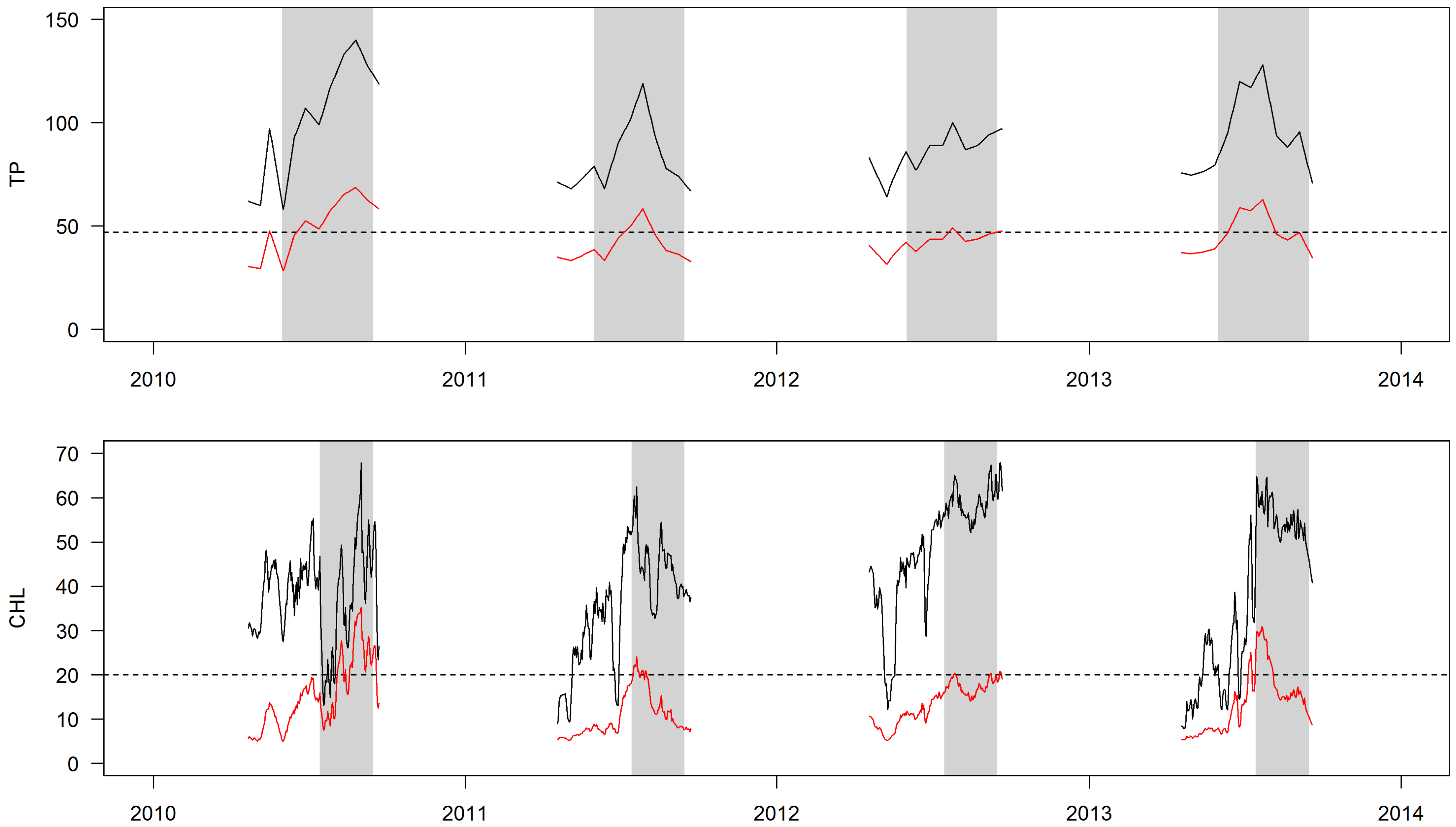

Figure 22. TP:CHL relationships for Wisconsin River reservoirs. All TP and CHL values are geometric mean values for assessment periods. Blue circles are reservoirs upstream of Petenwell Flowage. Circles and dashed lines for Petenwell, Castle Rock, and Lake Wisconsin represent current conditions (high TP/CHL) and SSC conditions (low TP/CHL). Gray circles are all other Wisconsin lakes and reservoirs that had at least six concurrent TP and CHL samples. Gray line is a 3rd-order polynomial regression fit to the log(CHL)~log(CHL) relationship for the gray circles.